



Electric Propulsion Technology Development for the Jupiter Icy Moons Orbiter Project

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Abstract

During 2004, the Jupiter Icy Moons Orbiter project, a part of NASA's Project Prometheus, continued efforts to develop electric propulsion technologies. These technologies addressed the challenges of propelling a spacecraft to several moons of Jupiter. Specific challenges include high power, high specific impulse, long lived ion thrusters, high power/high voltage power processors, accurate feed systems, and large propellant storage systems. Critical component work included high voltage insulators and isolators as well as ensuring that the thruster materials and components could operate in the substantial Jupiter radiation environment. A review of these developments along with future plans is discussed.

Introduction

In 2003 NASA's Project Prometheus began comprehensive efforts to develop advanced technologies for space use. Key to these developments is electric propulsion technologies that will enable new missions, particularly when combined with power generated by a space nuclear reactor.¹ The mission attributes that would be enabled by these technologies include more sophisticated active/passive remote sensing, greater launch window flexibility and spacecraft maneuverability at the destination planet or moon, and greatly increased science data rates. The first proposed mission application, the Jupiter Icy Moons Orbiter (JIMO), has focused on a 100 kW class spacecraft utilizing electric propulsion. Figure 1 shows an early concept of the JIMO Spacecraft.

Electric propulsion technology efforts discussed in this paper will deal only with Project Prometheus technologies under development for the proposed JIMO mission. Technologies directly related to enabling a JIMO-type mission include, but are not limited to, high power/high specific impulse gridded ion propulsion system concepts and NRAs, long life components and modeling, high voltage isolators/insulators, high power PPU options, and radiation hardened thruster components and materials.

Jupiter Icy Moons Orbiter: Challenges for Electric Propulsion

Overview

The proposed JIMO mission has two principle objectives.² The first is to tour and characterize three icy moons of Jupiter: Callisto, Ganymede, and Europa (fig. 2). The second objective is to demonstrate nuclear electric propulsion flight system technologies that will enable a range of revolutionary planetary and solar system missions.

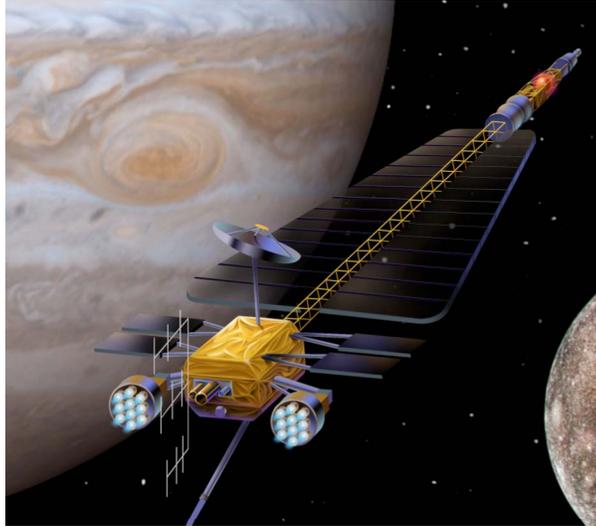


Figure 1.—Early Jupiter Orbiter Concept Spacecraft

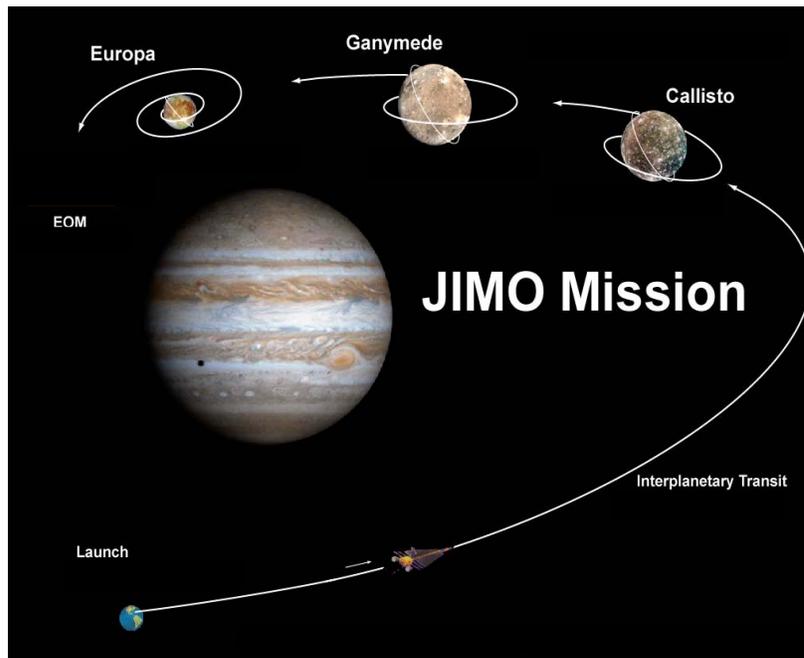


Figure 2.—Proposed JIMO Mission Phases

Specific requirements for JIMO are still under study by independent government and industry teams. However, top-level propulsion system characteristics have been identified:

- High power: 20 kW to 50 kW per thruster
- High specific impulse: 2000 sec to 9000 sec
- Long Life: A propulsion system capable of operating for 6 to 10 years
- Radiation Tolerance: The Jupiter environment requires very radiation resistant materials
- Technology Maturity: At Preliminary Design Review (PDR)
 - Development models complete (e.g., bread board hardware demonstration, high-fidelity computer models, etc.)

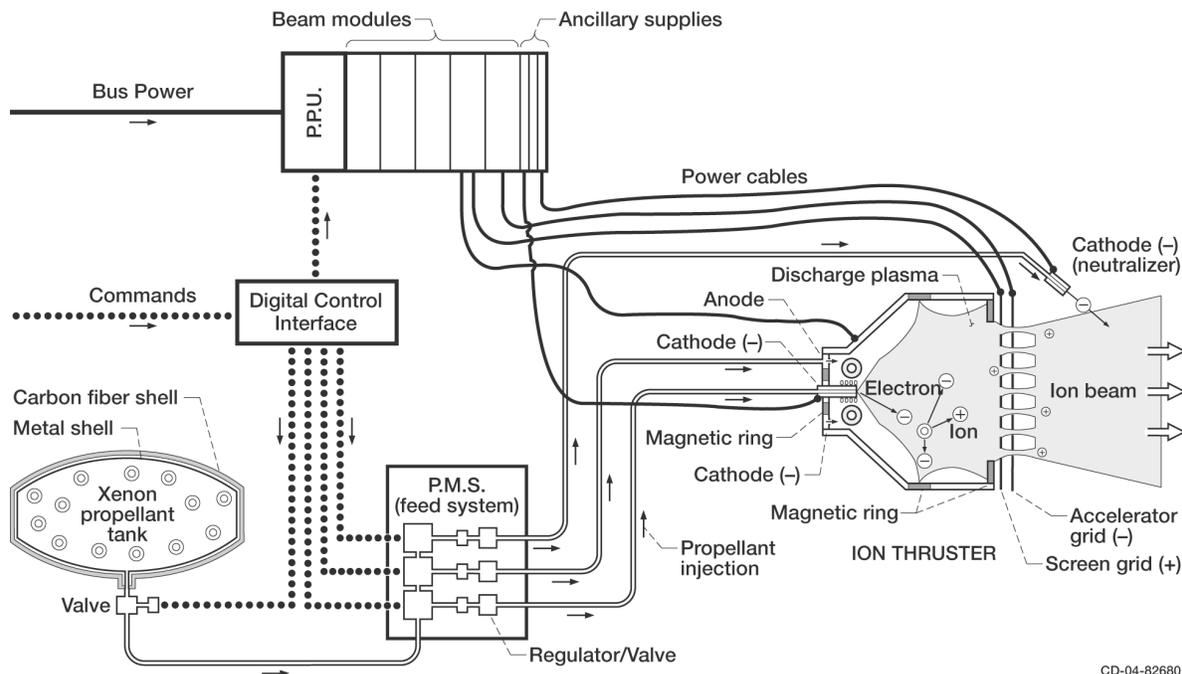
- All major risks for the technology development retired.
- All major manufacturing issues resolved
- Plans to accumulate life data that provides confidence that hardware will last for the life of the Project written and approved

Given these challenges, the JIMO project is developing an ion propulsion system as the most likely candidate for the JIMO application due to its maturity, high efficiency, demonstrated operational lifetime, and ability to provide the high specific impulses required by such high energy missions.

Ion Propulsion System Description

An overview of an ion propulsion system is appropriate before reviewing the JIMO propulsion challenges. Figure 3 shows the subsystems and functions of an ion system. An ion propulsion system provides the thrust for a spacecraft to maneuver in space by expelling a stream of high velocity ions. Since thrust = mass flow rate x exhaust velocity, the ion thruster provides thrust by providing high velocity exhaust (20,000 to 100,000 m/s exhaust velocities as compared to the maximum of 4500 m/s for chemical systems) while minimizing the mass flow rate (5 to 10 mg/s as compared to over 100 mg/s for a chemical engine with equivalent thrust). This saves fuel enabling high-energy space missions that could not carry enough chemical fuel to perform the mission. This high exhaust velocity derives its energy from some external source (unlike chemical propulsion which utilizes the energy of a chemical reaction from the fuel(s) themselves). Ion propulsion systems utilize an electrical energy source such as solar or in the case of the JIMO design a reactor. Despite the mass of this additional power system the high exhaust velocity or specific impulse of an ion thruster enables very high-energy mission ΔV s (10 to 60 km/s) to allow for deep space and multiple mission capability. To propel a spacecraft to its destination the ‘low thrust’ of the ion thruster must be provided for long durations (years) to provide the impulse needed. Hence the ion subsystems must provide very long operating lifetimes (years as compared to hours for chemical systems).

At the heart of an ion propulsion system (shown in fig. 4) is the thruster itself. The ion thruster produces ions used to provide thrust in the main chamber of the ion thruster through collisions between



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Figure 3.—JIMO Electric Propulsion System Functions

electrons, provided by either a hollow cathode or from a microwave source, and a neutral gas (xenon in this case) from the anode. The chamber is lined with magnet rings that confine the electrons enhancing the chance of collision with the neutral atoms. The ions are created at a high voltage relative to the spacecraft (1000 to 7000 Volts depending upon desired exhaust velocity, the higher the electrostatic potential the higher the exit velocity). At the exit of the chamber are two grids. The innermost grid is at the same high voltage as the discharge chamber cathode and is termed the screen grid. The outermost grid is set to a negative voltage (−200 to −800 Volts relative to spacecraft potential, again dependent on desired performance) and is termed the accelerator (accel) grid. The ions are accelerated between the two grids. Ions are focused so as not to collide with the grids, and they are expelled through circular apertures out of the thruster. The final component of the thruster is the neutralizer, another hollow-cathode or microwave source, which provides electrons to neutralize the ion beam. This prevents a charge from developing on the spacecraft allowing continued ion extraction.

While the ion thruster is designed to prevent direct impingement of the ions on the grids some ions unavoidably collide with neutral xenon atoms in the inter-grid volume and immediately downstream of the accel grid. Fast ions can exchange charge with slow neutral xenon atoms in these regions. These slow charge exchange ions can impinge on the accel grid hole walls, erode the material, and increase the hole diameter. Sufficiently large accel grid hole diameters will allow neutralization electrons to backstream in the discharge chamber. Grids must be designed to prevent this failure mechanism. Charge exchange ions produced downstream of the accel grid can also cause pit and groove erosion on the grid's downstream surface.³ Such unavoidable erosion is one of the life limiters of ion thrusters. The other causes for ion thruster failure are due to erosion or failure of the hollow-cathodes or failure of the high voltage isolation components due to temperature and contamination over time.

A power processor unit (PPU) is needed to convert the power from the spacecraft to the various voltages and currents needed by the ion thruster components. Most of the power is for the beam power supply, which powers the acceleration of the ions. Beam voltages vary from 1000 to 7000 Volts depending upon desired exhaust velocity. The other supplies are at lower voltages and supply power for the accel grid, cathode or microwave supplies. The main challenge for the power processor is to raise the voltage from the bus to the high beam voltage. Bus voltage type (AC or DC) and the level (100 to 400 V

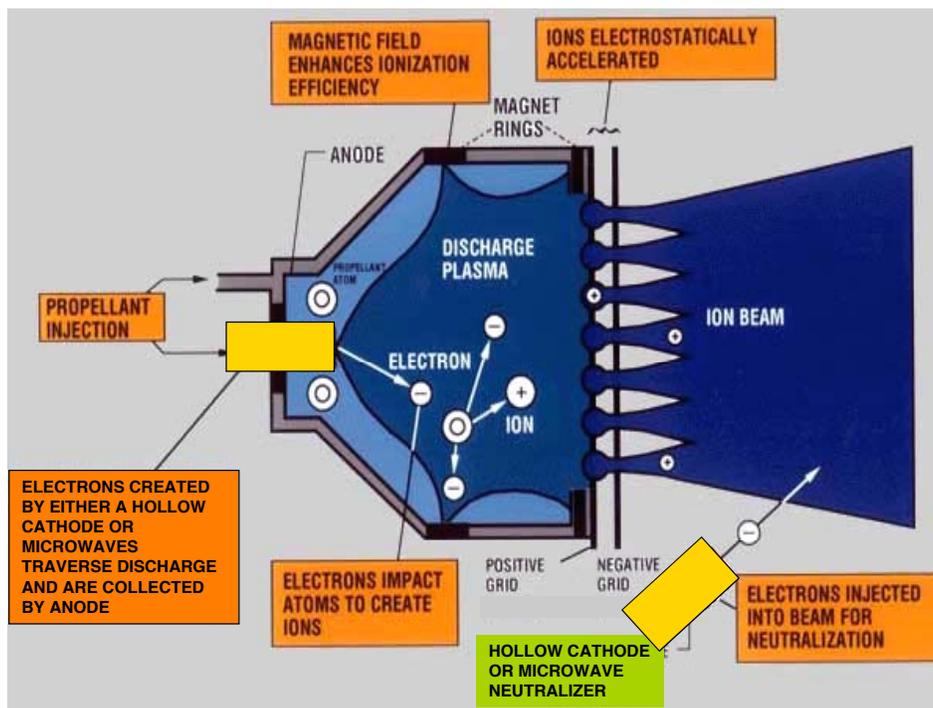


Figure 4.—Ion Thruster Operation

or more) will determine what voltage conversion approaches are applicable. In addition to the power processing function the PPU is often tasked with providing internal control of itself and parts of the feed system. Overall control of the PPU and feed system is a spacecraft function.

The propellant (again in this case xenon) must be fed at the appropriate rates to the main thruster chamber through the anode and the hollow-cathodes in the discharge chamber and the neutralizer or through the microwave neutralizer. These flow rates can differ by an order of magnitude but are very low, on the order of mg/s. Accuracy of the feed system is important with uncertainties of just a few percent required for proper thruster operation and reduced fuel usage.

The propellant itself must be stored for long periods by compact and lightweight propellant tanks. State of the art (SOA) xenon storage systems use carbon overwrapped pressure vessels (COPV) which store the propellant at high pressures ~2000 psia (as a supercritical gas).

JIMO Technology Challenges for Ion Propulsion

While the ion system appears to be the best option to meet the current JIMO propulsion requirements, based on the technology needs and schedule, the mission requirements still present several significant technology challenges for ion propulsion subsystems. Table 1 illustrates these challenges by comparing the technology needs for JIMO with current SOA ion thruster technology as represented by the NASA Solar Electric Power Technology Application Readiness (NSTAR) thruster recently flown on NASA Deep-Space 1 spacecraft.⁴ Figure 5 shows these challenges with respect to each electric propulsion subsystem. This comparison highlights technology areas requiring improvement for JIMO applications. Technology solutions that address each of these challenges are also included in table 1.

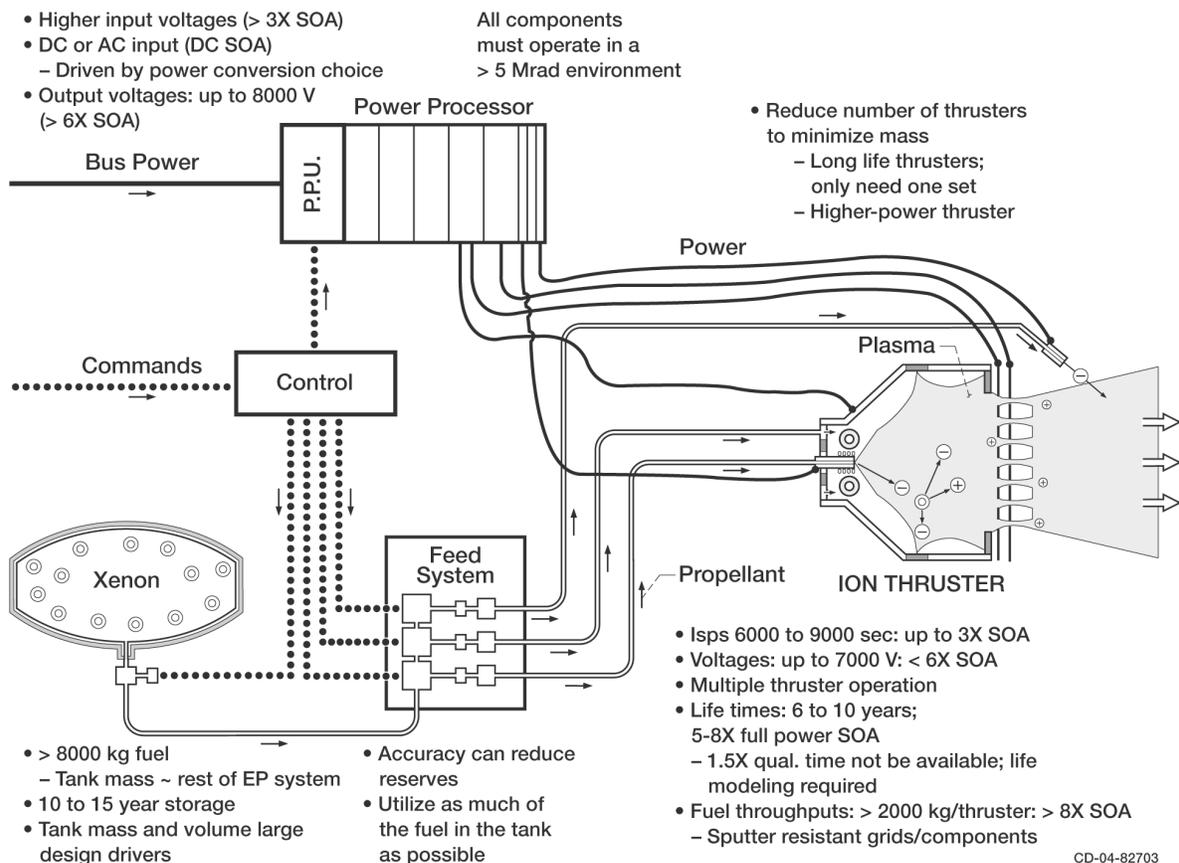


Figure 5.—JIMO Electric Propulsion System Challenges

TABLE 1.—JIMO ELECTRIC PROPULSION CHALLENGES VERSES SOA

SUBSYSTEM	PARAMETER	NSTAR (SOA)	JIMO	FACTOR OF IMPROVEMENT NEEDED VS SOA	DEVELOPMENT APPROACHES
Thruster	Power (kW)	2.3	20 to 50	9 to 22 X	Increase size and beam area of thruster either with larger circular or rectangular discharge chamber
	Specific Impulse (s)	3170	6000 to 9000	2 to 3 X	Raise Ion Beam Voltage
	Ion Beam Voltage (V)	1100	Up to 7000	> 6X	Increase Voltages to thruster, increase/improve isolator/insulator designs by increasing size and gap
	Ion Beam Current (A)	1.3	>8	>6X	Develop larger electron sources, either hollow cathode or microwave
	Xenon Throughput (kg)	229	>2000	>8.7X	Utilize erosion resistant grid materials made from carbon. Test and model for grid wear to predict life compliance
	Life at Full power (yr)	1.3	6 to 10	5 to 8 X	Develop long life hollow cathode or microwave sources. Use advanced isolator/insulator materials and designs to avoid long-time operation failure. Test and model failure mechanisms to predict life compliance
	Specific Mass (kg/kW)	3.6	<2	>1.8 X less	Develop larger thrusters that can provide full design life capability with one set
PPU	Input Voltage	80-160 VDC	100 to 600 VDC or VAC	1 to 4 X SOA	Utilize larger stepping transformers, either solid state (DC) or transformer pre-stage (AC)
	Output Power (kW)	2.3	20 to 50	9 to 22 X	Build higher power modules
	Beam Voltage (V)	1100	Up to 7000	> 6X	Improve module voltage stepping technology 6X
	Radiation Qualification Level (kRad)	100	>5000	50 X	Develop higher radiation hardened parts and shielding
	Specific mass (kg/kW)	6	< 4	1.5 X less	Develop larger beam modules
Fuel Sys.	Radiation Qualification Level (kRad)	100	>5000	50 X	Develop higher radiation hardened components
	Propellant Loading (kg)	80	>8000	100X	Develop larger supercritical storage tanks or develop cryogenic storage systems

For JIMO type applications the ion thruster must operate at ten times the input power or more of SOA thrusters at beam voltages over six times the SOA. These voltages are driven by the anticipated two to three fold increase in specific impulse needed to complete the high-energy mission relative to SOA thrusters. Multiple thruster operation will also be required. Thruster lifetime must also be increased five to eight times relative to full power SOA with xenon throughputs over eight times per thruster compared to the SOA. The various propellant isolators and insulators in the thruster must also perform for this long lifetime at up to six times the voltage utilized by SOA devices. The sources for electrons, both discharge and neutralization, must also support this increase in thruster lifetime. SOA cathodes, with demonstrated lifetimes of up to three years, have life-limiting characteristics including dissipation of the low work

function material that produces the electrons, coating of this low-work function material inside the cathode, and erosion of the cathode from ion bombardment in the ion chamber.

An approach to provide high power and long lifetime for ion thrusters is to build them larger. While obvious for the higher power operation, building a thruster larger than necessary – i.e., running it at lower currents, sometimes termed ‘derating’ – allows for more grid area for a fixed amount of xenon fuel throughput, thus reducing the erosion on the grids and allowing more life. This approach has been successfully used in both the NSTAR and NASA’s Evolutionary Xenon Thruster (NEXT) programs.^{4,5} However, enlargement of the thruster is not enough to handle the fuel throughput requirement of JIMO type applications. The grid materials need to be more resistant to erosion than the molybdenum materials used in the NSTAR program. Carbon based materials – such as Carbon-Carbon composites and Pyrolytic Graphite – are five to seven times more resistant to this erosion as compared to molybdenum. Thus one could expect a significant improvement in throughput over SOA. Both materials are being explored in current programs. To achieve longer lifetimes for the electron source two approaches are being made; mitigating the failure mechanisms of the hollow cathode and providing ionization and neutralization using a microwave source. A different type of cathode, termed the reservoir cathode and used successfully in the traveling wave tube industry, has inherently more low work function material and is being tested. A graphite keeper will serve as protection for the ion bombardment on the cathode.

This two prong approach for many of the challenges of the thruster design is being performed by the High Power Electric Propulsion System (HiPEP)^{6,7} and the Nuclear Electric Xenon Ion System (NEXIS)⁸ thruster projects as shown in figure 6. This approach mitigates development risk to the project. In many cases the subcomponent technologies could be combined together differently (e.g., hollow cathodes or microwave sources for either circular or rectangular discharge chambers) to provide additional risk reduction. Isolators and insulators will use new materials and be increased in size to handle the greater voltages. To avoid shorting due to deposition on the insulating material double shadow shields and special designs will be developed.

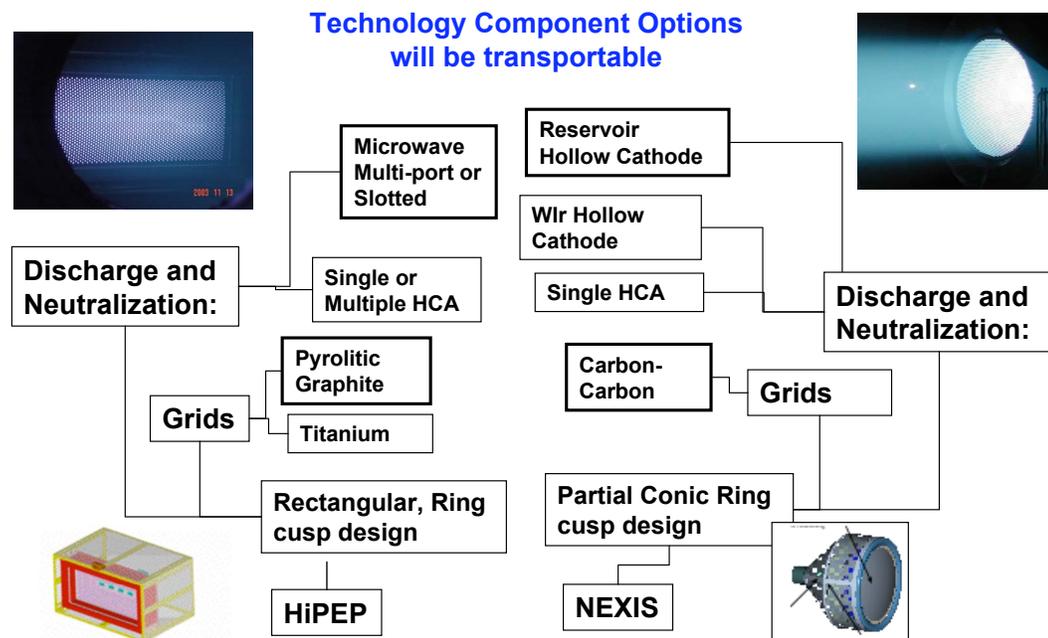


Figure 6.—JIMO Ion Thruster Technologies

The JIMO project is also evaluating the technology development for applicability to JIMO “follow-on” deep space science missions.² Such missions could require higher powers and different specific impulses. Both the HiPEP and NEXIS programs are addressing the potential growth requirement; HiPEP by providing a ‘stretchable’ rectangular design that can easily be upgraded in power, and NEXIS by increasing the power density. Such increases in power are easier if the required specific impulse (and thus voltage not current) also needs to be increased.

The power processor must provide these high thruster voltages (6X SOA) as well as handle input voltages from the bus of three or more times the SOA. In addition the PPU may utilize AC input as opposed to the DC SOA. If DC bus voltage current is chosen, higher voltage, higher power converter modules (perhaps 5 kW instead of the 300 W of NSTAR) would have to be developed. While these same converter modules could be used with AC bus voltage by just rectifying the voltage to DC, a more simple approach would be to utilize transformers to provide the higher beam voltages required then rectifying the voltage to DC. Such an approach would greatly reduce the parts in the PPU that would need to be radiation resistant.

The feed system must perform at accuracies similar to SOA while the storage system must handle ten to twenty times the SOA for very long storage times (over 10 years). With such large fuel loadings reducing the tank mass is important to minimize system mass. Current options for xenon storage range from carbon overwrapped pressure vessels (COPV), which store the fuel at high pressures ~2000 psia (as a supercritical gas) to cryogenically storing the fuel in liquid form. The latter is more complex as it requires power to eliminate unwanted boil-off but does provide for volumetric and mass savings. The supercritical COPV option would require larger Xenon tanks than have been built in the past.

All of the ion propulsion subsystems must endure an additional requirement, the extent of which, at least, is unique to the proposed JIMO mission: radiation. The moons of Jupiter, especially Europa, orbit well within the radiation belts of Jupiter. Similar to Earth’s radiation belts, but at much higher energy levels due to Jupiter’s correspondingly greater magnetic field, this radiation is caused by high energy electrons captured from the Sun. Estimates of the radiation levels, which would be experienced by the JIMO spacecraft, show levels of 5 Mrads or even higher, depending upon the exposure times. This radiation level exceeds that seen by geostationary spacecraft, which often use ion thrusters for stationkeeping, by at least an order of magnitude. A similar increase in relative radiation hardness compared to the NSTAR system is expected.

JIMO Electric Propulsion Team

A multi-faceted team of government, industry and academia is working on the JIMO electric propulsion technology challenges (fig. 7). The Electric Propulsion effort for the JIMO project is being led by GRC through preliminary design Phase B (2008) at which point it will transition to JPL oversight of industry for phases C and D. Each subsystem has a different lead but oversight for each subsystem will remain during the entire program. The responsibilities of GRC, JPL, and MSFC are shown in figure 8.² In phase B the industry prime will be selected and will be the responsible design agent for preliminary design of the propellant storage system. GRC will be the design agent as well as the collocation center for the thruster and power processor development. JPL will be the design agent for the feed system. For the final design phases (C and D) industry will be the design agent with government oversight.

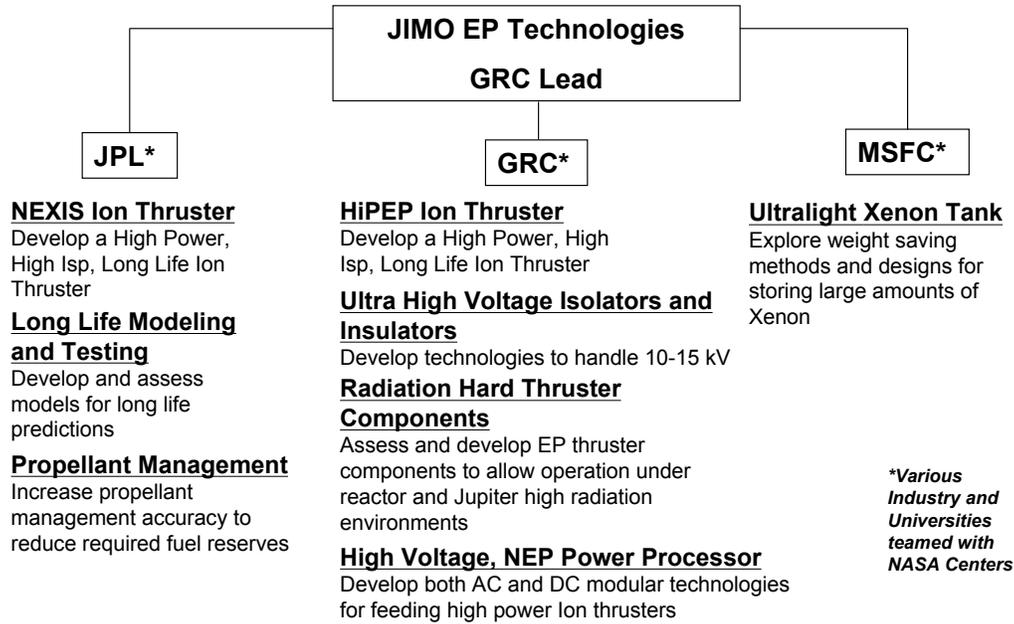
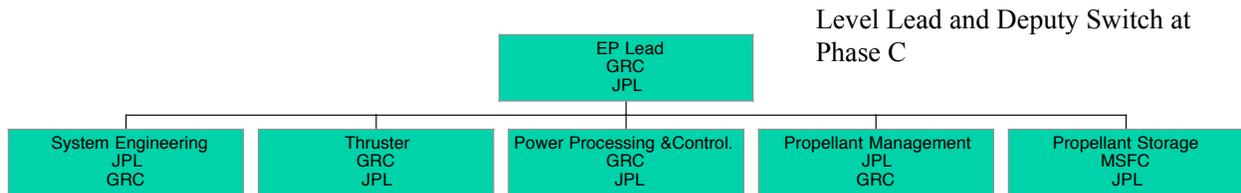


Figure 7.—JIMO EP Government Technology Developers



Sub-System Level Oversight to remain the same through launch

Figure 8.—JIMO Government Electric Propulsion Program Structure

JIMO Electric Propulsion Technology Efforts

ROSS 2002 NRA In-Space Propulsion Technologies

Before the start of Project Prometheus and the JIMO project, the ROSS 2002 NRA for In-Space Propulsion Technologies competed the following topic: “High Power Electric Propulsion for Near-Term Nuclear Systems”. The solicited activities were to lead to a laboratory demonstration of an EP system that met the following performance objectives:

- Thruster Power: Between 20 kW to 50 kW (total vehicle power 100 kW)
- $6000 \text{ s} < I_{sp} < 9000 \text{ s}$
- Efficiencies (Thruster and PPU) > 65 percent over full operating range
- Low Mass-to-power ratio
- EP system architecture, component lifetime, and reliability to support a single thruster throughput > 50 kg[fuel]/kW

The efforts were to “lead to a full scale demonstration of an innovative EP thruster within three years”. With the start of Project Prometheus two of the selected NRAs have been transitioned to the Prometheus program and consequently the JIMO project. The following section summarizes the two successful proposals adopted by the JIMO project: a NASA Glenn Research Center led team with its High Power Electric Propulsion System (HiPEP) and a Jet Propulsion Laboratory led team with its Nuclear Electric Xenon Ion System (NEXIS) thruster.

High Power Electric Propulsion System (HIPEP)

HIPEP, awarded to a GRC led team, is to demonstrate an ~8000s, 25kW engine system. The design concept includes either microwave or hollow-cathode discharge sources and neutralizers and a rectangular geometry that is more easily scaled than a cylindrical engine.⁶ Specific aspects of the HiPEP program are described more thoroughly elsewhere.^{6,7,9,10,11,12,13,14,15}

This year the JIMO-HiPEP team explored various plasma production options including DC hollow cathode and AC microwave discharge options.⁷ Both were used with the HiPEP thruster, demonstrating the applicability of either discharge approach to the rectangular concept. The microwave concept demonstrated up to 16 kW powers limited only by the available microwave supply (fig. 9). The hollow-cathode approach demonstrated powers up to 40 kW and efficiencies in excess of 72 percent for specific impulses between 6000 and 10,000 seconds; at the higher powers the efficiency was above 75 percent (fig. 10). The rectangular thruster concept was validated for both approaches. The rectangular shape can enhance packaging of multiple thrusters on a spacecraft. Many thrusters can be installed next to each other, minimizing structural elements and providing a dense cluster of aligned beams. This rectangular shape will also allow for easy scaling of the thruster, both the chamber and the grids, by ‘stretching’ without extensive redesign. Early testing in the year utilized curve titanium grids to demonstrate electrostatic design. Later testing successfully demonstrated flat pyrolitic graphite grids that will greatly increase the thruster’s lifetime.⁹ This grid material and geometry is projected to provide the 100 kg/kW xenon throughput at both 8000 and 6000 seconds.^{9,10,11,12,13} Analysis by Aerojet has projected that such flat grids, with the proper flight designed thruster, can survive launch with margin.¹⁴ Two different neutralizer concepts were also investigated by HiPEP this year; one using conventional hollow cathodes and two using microwave sources.

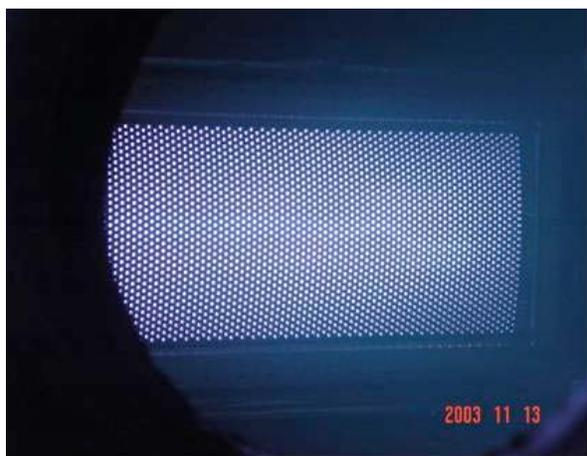


Figure 9.—HiPEP Operation with Microwave Source: Up to 16 kW Demonstrated

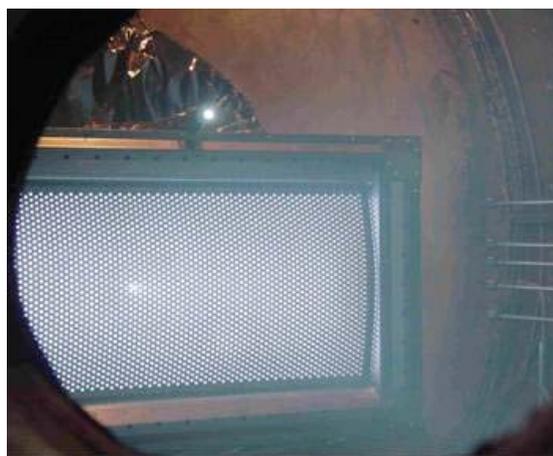


Figure 10.—HiPEP Operation with Hollow Cathodes: Up to 40 kW Demonstrated

Based on the success of the HiPEP lab model testing, two NRA development models (or NRA-DM) are being built to address various form, fit, and function challenges based on the NRA requirements. The first NRA-DM will be used in a 2000 hr wear test later this year. This test, while short compared to the required 6 to 10 year lifetime expected for JIMO, will demonstrate the ability of the thruster design to operate for long periods, uncover any unexpected problems, and begin to assess the long life features of the thruster. The test will be conducted in Vacuum facility 6, a 8 x 20 m facility with a pumping speed of 300 kl/s on xenon. Such a facility should keep the backsputter of tank wall material (also graphite in this case) to a minimum of 1 to 2 micron/kh. The second HiPEP NRA-DM will be built by Aerojet next year and will be used for performance and integration testing.¹⁵

Nuclear Electric Xenon Ion System (NEXIS) Thruster

The NEXIS project, awarded to a JPL led team, is concentrating on a ~7500s, 20 kW engine system with focus on improving life limiting components by investigating cathode/neutralizer improvements and carbon composite grids.⁸ Specific aspects of the NEXIS program are described more thoroughly elsewhere.^{8,15,16}

This year the JIMO-NEXIS team demonstrated a large 65 cm circular lab model ion thruster as well as a reservoir cathode. This cathode was successfully run in a 2000 hr test by MSFC. Such cathodes can provide for much more low work function material to provide for long cathode lifetimes. The NEXIS thruster demonstrated powers up to 27 kW and efficiencies in excess of 75 percent for specific impulses between 6500 and 8700 seconds (fig. 11). The large circular thruster demonstrated a multi-magnet ring approach as well as flat carbon-carbon grids. For flight a dished set of grids has been analyzed and is predicted to survive launch loading. This grid material and geometry is projected to accommodate the 100 kg/kW xenon throughput margin required.⁸

Based on the success of the NEXIS lab model testing NRA development models (or NRA-DM) are being built to address various form, fit, and function challenges based on the NRA requirements. The first NRA-DM will be used in a 2000 hr wear test later this year. This test, while short compared to the required 6 to 10 year lifetime expected for JIMO, will demonstrate the ability of the thruster design to operate for long periods, uncover any unexpected problems, and begin to assess the long life features of the thruster. The test will be conducted in Vacuum facility 148-1, a 3.3 x 10 m facility which will use low sputter materials and a liquid nitrogen cooled target to absorb the 20 kW beam. Additional NEXIS NRA-DMs will be built next year and will be used for performance and integration testing.

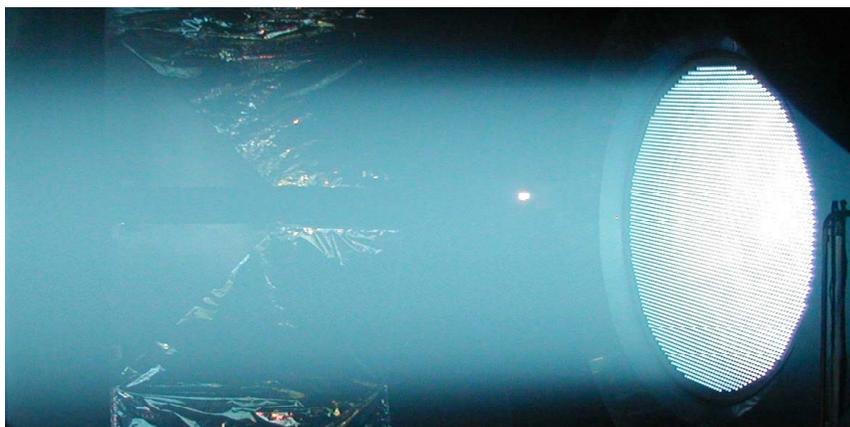


Figure 11.—NEXIS Ion Thruster: Up to 27 kW Demonstrated

Very High Voltage Propellant Isolators and Insulators for Gridded Ion Thrusters

The electrical isolation between spacecraft-potential ion thruster propellant tanks and the discharge chambers has always been a source of reliability and durability concern. Similarly, the need to mechanically support the thruster body and ion optics with high voltage differences from adjoining components represents a trade off challenge predominantly involving size, weight, structural considerations and durability. The NASA Solar Electric Propulsion Technology Readiness (NSTAR) program ion propulsion system used on the Deep-Space 1 spacecraft required xenon propellant isolation and insulation for potential differences of 1100 volts.

Ultra High Voltage (UHV) propellant isolators and electrical insulators are needed for the ion thrusters to enable the high power missions proposed by Project Prometheus to allow the higher specific impulse thrusters to operate with their xenon propellant tanks at ground potential. It is anticipated that electrical isolation of 6500 volts will be required and that a 15,000 volt stand off should be required to assure a reasonable safety margin. An array UHV xenon propellant isolators and insulators are to be constructed and evaluated under normal and envelope of potential operating conditions to quantitatively measure limitations and safety margins.¹⁷ Performance and durability testing will be conducted under a variety of flow conditions, temperatures, in vacuum and pressures to measure leakage currents (fig. 12). Both high and low-pressure isolator designs have been included. Shadow shield design, tolerance to contamination and Pashen breakdown will also be evaluated for both UHV propellant isolators and insulators. Modes of failure of xenon propellant isolators and insulators will be investigated to allow a protocol to be developed to enable accelerated durability testing to be accomplished. The variety of tests of isolator and insulator concepts will be compared with stretched segmented NSTAR-type isolators and large-gap NSTAR type insulators to identify and develop the next generation of isolators and insulators to best suit mission needs. A down selection to two concepts has been performed for the insulators; wavy or grooved external surface ceramic-to-metal sealed alumina “H” cross section cylinder and smooth external wavy surface ceramic to metal sealed alumina “H” cross section. Both concepts are being constructed for performance and durability evaluation. Eight concepts for the xenon propellant isolators were down selected for fabrication and experimental evaluation. Final selection of isolator and insulator will be based on a combination of factors including: performance, reliability, durability, size, range of operating pressure and cost.

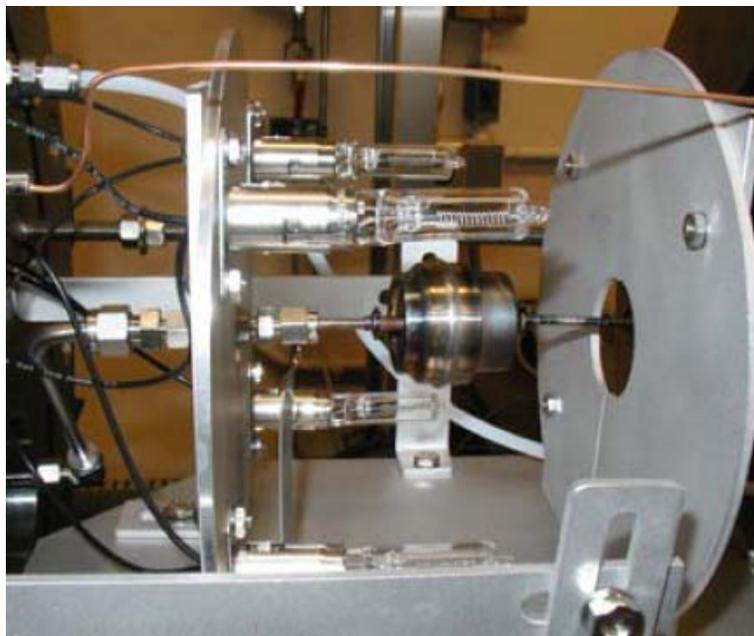


Figure 12.—High Voltage Propellant Isolator in Test Configuration

Ion Engines Life Modeling and Testing

Proposed NEP missions will require electric propulsion subsystems to operate for more than 6 years, much longer than previously demonstrated for thruster technology. The life of the thruster must be validated during the technology selection and development process using a combination of analytical and numerical models, experimental data, and accelerated life test results. Consequently, comprehensive codes and experimental capability will be required to validate the electric propulsion service life. Specific aspects of the life modeling program are described more thoroughly elsewhere.^{18,19,20,21,22,23,24,25}

The Ion thruster life validation approach is to develop, validate and use a suite of “Qualified codes”. Based on various past ion thruster tests of which the longest was 30,000 hours²⁶ it is felt that most of the major ion thruster life limiting processes have been identified. The codes needed to predict the life limiting processes range from physics based models to deterministic. The codes will be “Qualified” by an independent technical review board that will evaluate the models by comparisons with results from detailed testing. The board will also determine the range of applicability of the codes explicitly. Maintenance of the validation will be in the form of a formal “Design Basis Document” which will be configuration controlled by technical justification of all the numbers that go into the analysis (e.g., cross sections, material properties, etc. with references). Spiral development and comparison with results of wear tests will provide for several stages of improvement of the codes from subcomponent to system level.

This year a component, processes, & preliminary assessment will be held. The goals of the assessment include identification and description of the physical mechanism of critical life limiting processes, and a preliminary assessment of each component’s life. The ion thruster components include ionization source, discharge chamber, ion optics, and neutralizer. Success criteria for the review will include independent review board concurrence that the preliminary thruster life models used in the JIMO Preliminary Life Modeling Document and the JIMO system analysis are conceptually sound. Some of the components to be modeled and the processes addressed are shown in table 2.

TABLE 2.—THRUSTER LIFE MODELS AND MECHANISMS

Model	Contains or addresses
Cathode Insert	Insert temperature and work function
	Insert barium depletion with time
Cathode Interior Region	Neutral gas density and temperature
	Plasma generation, density, temperature and transport
	Thermal model and self heating
Orifice Region	Neutral gas density and heating
	Plasma generation, potential and transport
	Ion bombardment of the orifice plate
Keeper Region	Neutral gas density
	Ion current and energy exiting this region
	Keeper erosion model
	Plasma generation and flow into discharge chamber
Discharge Chamber Region	Neutral gas density
	Magnetic field distribution
	Plasma generation
	Plasma confinement and transport to grids
Grid Region	Ion optics (2 and 3 D models)
	Screen wear
	Accel grid barrel and downstream erosion
	Sputtered material transport model
	Material redeposition and flaking
Microwave generator	Plasma generation by microwaves
	Coupling and reflected power (VSWR)
	Antenna-plasma interaction

Radiation Hardened Materials and Components

Among the unique challenges posed by the JIMO project is the expected high radiation expected in Jupiter space (especially at targets such as Europa where the radiation environment could contribute >5 Mrads radiation to the JIMO spacecraft). This ionizing radiation environment necessitates evaluation and demonstration of ion thruster materials and components that are tolerant to these environments.

Ion thruster materials and components must be able to start up and operate, without failure or unacceptable loss in performance, in the presence of ionizing radiation anticipated during the JIMO mission. Specific ion thruster materials and components are being identified that are thought to be vulnerable to degradation. Investigations have involved literature studies on material properties as well as materials and component testing using ionizing radiation to validate acceptable performance and durability of selected critical materials and components. Electrical properties such as dielectric strength, resistivity, surface resistance, dielectric constant, and work function are being considered for selected components. Mechanical properties such as dimensional stability, coefficient of thermal expansion, elastic modulus and elongation to failure are also being considered for selected components. Functional characteristics such as electrical breakdown strength and leakage current during operation in a mission representative ionizing radiation environment are under assessment. Retention of internal thruster sputter deposits subjected to radiation exposure will also be evaluated.

An assessment to prioritize the impacts of the radiation environment has been done (fig. 13). The impact was assessed as the (Probability of degradation) x (Consequence if material or component degradation occurs) with the probability of material or component degradation defined as 4 = Certainty, 3 = High probability, 2 = Moderate probability, 1 = Low probability, 0 = Negligible and the consequence if material or component degradation occurs defined as 4 = Thruster failure, 3 = Significant loss in

	Cathodes	Neutralizer	Ion Optics	Propellant Isolators	Grid Insulators	Magnets	Wiring/cables	Coated Anode Segment	Microwave generator	Gas Flow Control Valves
Electrical Characteristics										
Dielectric Strength										
Resistivity										
Resistivity vs. Applied Field										
Surface resistance										
Dielectric Constant										
Work Function	3	3								
Mechanical Characteristics										
Dimensional stability										
CTE										
tensile strength							8			
Elastic Modulus										
Elongation to failure							8			
Other Functional Characteristics										
electrical breakdown while operating in radiation environment			8	6	6		2		6	
leakage current while operating in radiation environment				2	2		2			
Ability to operate following radiation exposure	4	4					2		3	6
Radiation Degradation of Magnetic Field						6				
Retention of Sputtered Coatings due to operating in radiation environment								2		

Figure 13.—Impact Assessment of Thruster Characteristics to Radiation Environment

durability or performance, 2 = Moderate loss in durability or performance, 1 = Small loss in durability or performance, 0 = Negligible consequence. As can be seen from the figure, the greatest areas of perceived concern include wiring/cables, ion optic operation, and several subcomponents such as magnets, isolators/insulators, flow control valves, and the microwave generator. Cathodes are deemed susceptible to a lesser extent.

One test being conducted in the near term seeks to assess the impact of ionizing radiation on operation of the thruster itself. The ionizing radiation at Jupiter could cause a high rate of grid electrical breakdown that could prevent proper thruster operation. Laboratory testing is planned to investigate ionizing radiation effects on grid electrical breakdown using an $^{84}\text{Po}210$ 5.3 MeV Alpha particle source and a partial vacuum with xenon flow between biased grids. Testing will evaluate rate of electrical breakdown as a function of thruster operating conditions and radiation environment. The parameters to be assessed include: grid voltage gradient, pressure of xenon in grid gap, and flux of ionizing radiation particles. The laboratory conditions will be correlated to space environment conditions expected for the various segments of the proposed JIMO mission.

High Power, High I_p Gridded Ion Power Processing Units

An effort to provide power processing unit (PPU) modular technologies for several possible PPU architecture options to satisfy potential Jupiter Icy Moons Orbiter (JIMO) mission thruster requirements is being conducted by a GRC-led team.²⁷ The effort will culminate in breadboard lab articles.

State of the art PPUs use DC-DC converters or power supplies to transform power from its input into isolated and regulated power at the levels required by a thruster. In addition, they provide high voltage recycle control to extinguish possible thruster arcs, telemetry interface with the spacecraft, and thruster cross-strapping when multiple thruster are operated from one PPU. A state of the art PPU contains thousands of electronic parts and a peak efficiency of 94 percent. High power electric propulsion systems pose unique design challenges such that scaling SOA PPUs for JIMO class missions would represent an increase in parts count and heat losses that could severely impact spacecraft mass and reliability.

Several power conversion system options are being explored for the proposed JIMO mission. These options include DC or AC power, perhaps at higher than SOA voltages. If DC bus voltage current is chosen, higher voltage, higher power converter modules (perhaps 5 kW instead of the 300 W of NSTAR) will have to be developed. While these same converter modules could be used with AC bus voltage by just rectifying the voltage to DC, a more simple approach would be to utilize transformers to provide the higher beam voltages required then rectifying the voltage to DC. DC power for the thruster is obtained by rectifying and filtering the AC inputs. This could potentially result in a simpler and more efficient PPU with only hundreds of parts and an efficiency as high as 98 percent.

Other issues include the availability of radiation-hardened, high power components for the PPU, regardless of the selected architecture. The radiation hardened electronic components necessary for the PPU modules will be supplied by the other tasks in the JIMO program. Finally, while high voltage thruster faults (recycles) have not been problematic in previous programs due to the lower voltages and power levels, in the case of an NEP-powered mission, the stored energy in the power supplies may be sufficient to damage the thruster in the event of a fault, and special quenching circuitry may be needed.

The current PPU effort has focused on developing new technology components for AC and DC input high power electric propulsion power processing systems.²⁷ Each approach, AC or DC, have specific technology development needs. Such technologies, once developed, can then be combined with state-of-art systems to develop JIMO power processing units.

Recently efforts to breadboard a sub-scale, proof-of-concept beam power supply have been successful (fig. 14). Recent testing of the beam module has demonstrated low noise and ripple. In addition a DC powered accel supply was built and successfully tested. Current efforts consist of fabricating additional beam modules to create a complete beam supply. Combined with the accel supply this partial PPU will be tested with a thruster in the late fall.

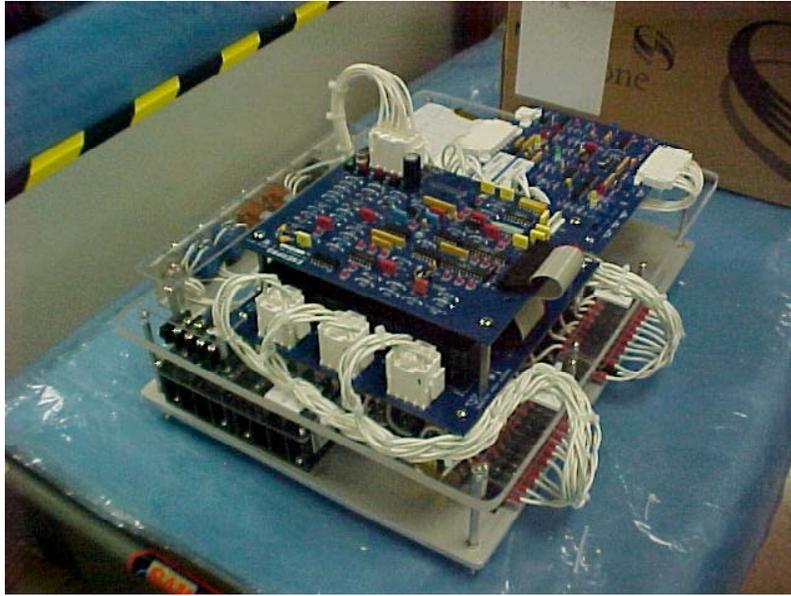


Figure 14.—Regulated Beam Supply Module

Propellant Management

The proposed JIMO mission would require significant fuel loadings of 8000 kg of xenon or more and storage times of over ten years necessitating feed system components with high accuracy and long life. A JPL-led trade study was performed on xenon feed system designs with the goal of reducing the flow uncertainty to ± 1 percent over a 10-year mission. The state of art system used by NSTAR was a bang-bang regulation system that, while very rugged, is not practical for JIMO application due to the large number of cycles required and the wasted volume of a plenum tank. Various options to provide a highly accurate, rugged feed system exist using components that should be available but for the intense Jupiter radiation environment. This high radiation environment will impact several components, pressure transducers in particular. Technology development to harden such components is being performed elsewhere in the JIMO project. Several options have been proposed for systems that could utilize most of the propellant in the tank by providing ancillary systems for processing the low pressure xenon in the tank at the end of the mission. Such options have not yet been investigated.

Propellant Storage

While several studies of propellant tank options have been performed this year, technology development efforts are being delayed until the industry prime can participate.

Future Plans

Over the next few years the preceding electric propulsion technology products will be phased into the JIMO development program. Top level roadmap and schedule showing the overall phases of the JIMO project and the corresponding electric propulsion system phase and area are shown in figures 15 and 16, respectively. Beginning next year the JIMO project is planning to enter phase B with a Preliminary Mission and System Review (PMSR) as well as the prime contractor.² At this time the preliminary design requirements will be set at the PMSR. These requirements will be used to perform the preliminary design of all of the electric propulsion subsystems.

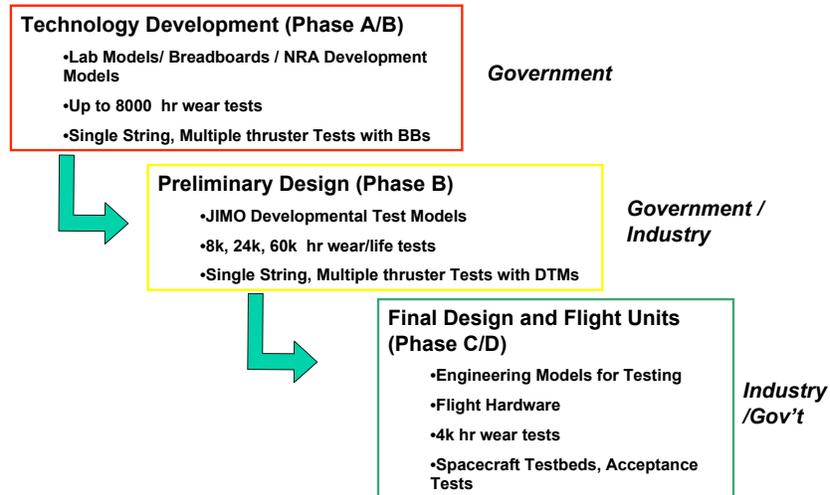


Figure 15.—Electric Propulsion Development by Project Phase

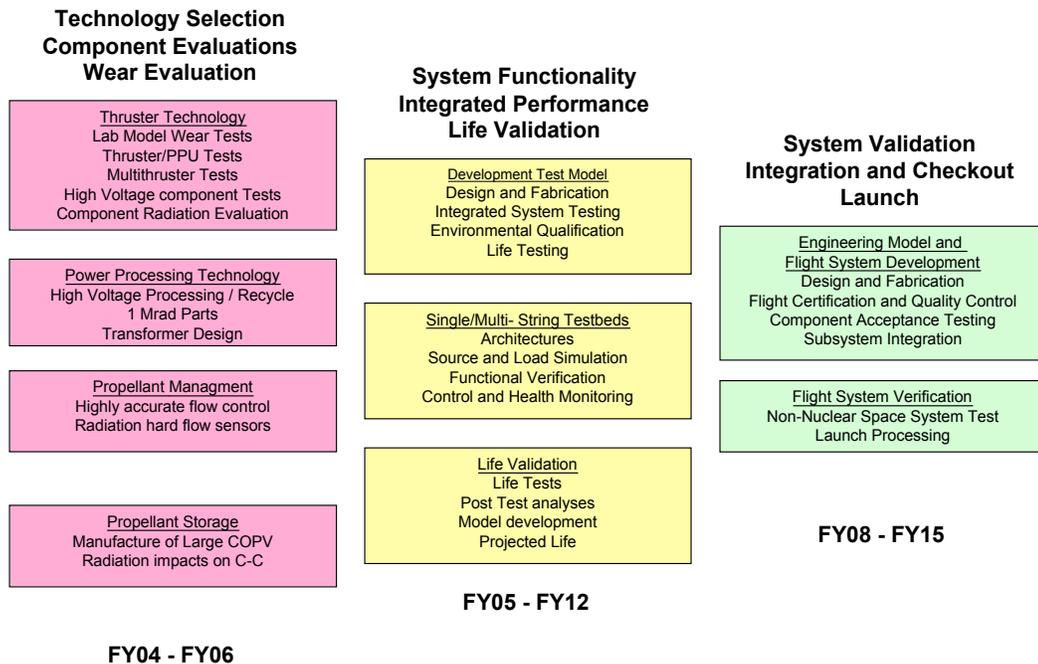


Figure 16.—JIMO Electric Propulsion Development by Area

This preliminary designs or JIMO Development Models (DMs) will then be fabricated and tested. Development Models, also defined as Development Test Models by the JIMO project, should have flight-like form, fit, and function, but do not have to be an exact duplicate of a flight unit in these respects. Hence the JIMO DMs will address the preliminary design requirements, but the Engineering Models of phase C will address the Final Design requirements. Culmination of the preliminary design phase B is at the Preliminary Design Review, planned for July 2008.

The technology portion of the program will continue to work with breadboards and the NRA DMs (DMs based on the NRA requirements as previously described). After wear testing and various NRA DM

integration tests a selection of the suite of primary technologies to be used for the preliminary design will be chosen. This selection is currently planned for late FY 2005. The current method of selection will utilize TQM methods and an independent review board to help determine the best technology choices. Some backup technologies may still be carried to mitigate risk.

Various tests planned for the EP technologies over the next few years include 2000 hr wear tests of the NRA-DM thrusters, an 8000 hr wear test of an NRA-DM thruster, an NRA-DM thruster test with a PPU Breadboard, and multiple thruster testing to determine the impacts of running thrusters in close proximity on the spacecraft and of running next to each other. The wear tests are planned to occur at GRC and JPL. Integration tests will culminate in a single string test of the power conversion system, power management and distribution system, power processing, and NRA thruster. Plans are to use two large vacuum facilities at GRC to perform these multi-thruster and integration tests.

Conclusions

This year the Jupiter Icy Moons Orbiter Project, an element of NASA's Project Prometheus, continued efforts to develop electric propulsion technologies for the proposed Jupiter Icy Moons Orbiter and follow-on science missions for solar system exploration. The technologies under development for JIMO include 20 to 50 kW gridded ion propulsion systems, high voltage power processors, radiation hardened components, and long life modeling.

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